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Modeling Improvements and Users Manual for Axial-Flow Turbine Off-Design Computer Code AXOD

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ABSTRACT

An axial-flow turbine off-design performance computer code used for preliminary studies of gas turbine systems was modified and calibrated based on the experimental performance of large aircraft-type turbines. The flow- and loss-model modifications and calibrations are presented in this report. Comparisons are made between computed performances and experimental data for seven turbines over wide ranges of speed and pressure ratio. This report also serves as the users manual for the revised code, which is named AXOD.

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SUMMARY

An axial-flow turbine off-design computer code used for preliminary studies of gas turbine systems was modified and calibrated based on the experimental performance of large aircraft-type turbines. The flow- and loss-model modifications and calibrations are presented in this report. Comparisons are made between computed performances and experimental data for seven turbines over wide ranges of speed and pressure ratio.

With regard to the flow model, the continuity calculation was modified to include a flowpath slope derived from an axial-chord length correlation and a flow coefficient having an input design value with a built-in reduction of 2 percent between low pressure ratio across a blade row and choke. The loss model was improved by revising the blade-row efficiency calculation methodology and calibrating the incidence-loss law. Blade-row efficiency, previously maintained constant, was reduced at blade-row exit velocities beyond choke, reaching a reduction of 2 percent at an exit Mach number of about 1.4. A positive-incidence exponent of 3 and a negative-incidence exponent of 4, along with optimum incidence angles of -4 degrees for low-pressure type turbines and -6 degrees for high-pressure type turbines, yielded best results for the incidence cosine law.

Using the revised off-design performance model, computed flows and efficiencies were compared with experimental values for seven aircraft-type turbines of varied design characteristics and operating over wide ranges of speed and pressure ratio. The experimental values were generally within 1 percent of the computed values and seldom beyond 2 percent. Maximum discrepancies between computation and experiment were reduced to about half of those from the original performance model.

This report also serves as a user's manual for the revised code, which is named AXOD. Program input and output are described, and samples are included.

INTRODUCTION

Preliminary studies of gas turbine systems require many repetitive calculations of geometry, design-point performance and, particularly for propulsion systems, off-design performance for all the components. An analytical procedure and a computer program to calculate the off-design performance of axial-flow turbines are described in reference 1. Flow and loss models presented therein were used to compute performance over ranges of speed and pressure ratio.

The performance model of reference 1 was based on axial flow (i.e., no radial component of velocity) in annular sectors of constant span fraction distribution. A subsequent modification provided a correction to account for flow entering and leaving sectors within each blade row. Continuity was satisfied using the geometric flowpath radii and blade angle input with no blockage correction. The loss model consisted of blade-row inlet energy recoveries that were proportional to a constant recovery efficiency and an incidence cosine law, blade-row kinetic energy efficiencies that were maintained constant, and a stage test factor to account for other losses and discrepancies. A recent review of this performance model resulted in concerns that the axial-flow assumption was not adequate for turbines with high flowpath slopes, and that the loss model had not been sufficiently tested and calibrated with experimental data. An investigation was, therefore, performed to evaluate the referenced off-design performance model and to modify and calibrate it as required.

This report presents the turbine off-design performance model modifications and calibrations, and also serves as the user's manual for the revised code, which is named AXOD. Experimental data for large aircraft-type turbines, both high-pressure and low-pressure designs, provided the data base for improving the performance model. The computed flows and efficiencies for seven turbines, three of which are from the NASA Energy Efficient Engine program, are presented and compared with experimental values. Program input and output are described and samples are included.

SYMBOLS

A_{an}	annulus area, ft^2
c_f	flow coefficient
c_p	heat capacity, Btu/(lb)(^oR)
g	gravitational constant, 32.17 (lbm)(ft)/(lbf)(sec^2)
Δh	specific work, Btu/lb
i	incidence angle, deg
J	energy conversion constant, 778 (ft)(lb)/Btu
k	correction coefficient
N	rotative speed, rpm
p	static pressure, psi
pr	pressure ratio
P	total pressure, psi
T	total temperature, ^oR
U	blade speed, ft/sec
V	gas velocity, ft/sec
w	mass flow rate, lb/sec

α flowpath angle of inclination, deg

β flow angle from axial direction, deg

γ specific heat ratio

δ ratio of inlet total pressure to standard pressure (14.696 psi)

ε specific heat ratio correction to mass flow rate

η efficiency

θ squared ratio of critical velocity based on turbine inlet temperature to critical velocity based on standard temperature (518.7°R)

ρ density, lb/ft^3

T torque, (lb)(ft)

Subscripts:

b blade row

ex blade-row exit

f relating to flow coefficient

hi high end of correction range

i sector index

id ideal

in blade-row inlet

lo low end of correction range

opt optimum

p pitchline

r root

rec recovered or recovery

ts based on inlet-total to exit-static pressure ratio

tt based on inlet-total to exit-total pressure ratio

u tangential component

x axial or meridional component

η relating to efficiency

Superscript:

exp exponent in equation (5)

n incidence cosine law exponent

OFF-DESIGN PERFORMANCE MODEL

Presented in reference 1 is an analytical procedure for computing the off-design performance of axial-flow turbines. This analytical procedure was based on axial flow (i.e., no radial component of velocity) in annular sectors of constant span fraction distribution. This generally resulted in a shift in flow fraction distribution among the sectors within a blade row, thus producing a possible error in energy and ideal-entropy conservation (see ref. 1). To compensate for this, a subsequent modification was made that corrected the blade-row exit flow and state variables for each sector to values based on the same flow fraction as had entered.

This section describes the flow and loss models used to compute off-design performance. The reference model is presented first and then the recent modifications are described.

Reference Model

The flow and loss models defining the analytical procedure of reference 1 are presented in this section. All velocities and flow angles are relative to the particular blade row (i.e., absolute values for stators and relative values for rotors).

Flow.- Continuity was computed at each blade-row exit as

$$w = \sum \rho_i V_{x,i} A_{an,i} \tag{1}$$

where

$$V_x = V \cos \beta_{ex} \tag{2}$$

and

$$V^2 = V_x^2 + V_u^2 \tag{3}$$

Since V_x must be the axial component of velocity to satisfy equation (1) and the meridional component to satisfy equation (3), the meridional velocity had to be purely axial (i.e., no radial component) to satisfy both. The angle β_{ex} was the given exit angle for the blade row.

Loss.- There were three types of losses considered for the off-design performance model: a blade-row inlet loss, a blade-row loss, and a stage test loss. The blade-row inlet loss accounts for area-constriction and incidence effects at the inlet to each blade row by producing a reduction in blade-row inlet total pressure. The blade-row loss accounts for frictional and secondary losses within the blade row by a reduction in exit velocity. The stage test loss can be used to account for losses not directly accounted for by the velocity diagrams.

Blade-row inlet loss was represented by a blade-row inlet kinetic-energy recovery efficiency defined as

$$\eta_{rec} = V_{rec}^2 / V_{in}^2 = \eta_{rec,opt} \cos^n (i - i_{opt}) \tag{4}$$

The recovered kinetic energy from equation (4) was used to compute a reduced total pressure at the blade-row inlet. Values for optimum recovery efficiency, optimum incidence angle, and cosine-law exponent must be provided by the user. Optimum recovery efficiencies and optimum incidence angles can be specified for each sector of each blade row. Different exponents can be specified for positive and negative incidence. An exponent of 2 corresponds to a recovery of the kinetic-energy component parallel to the optimum flow angle and, therefore, a loss of the component normal to the optimum flow angle. A higher exponent results in a higher loss.

Blade-row loss was represented by a blade-row kinetic-energy efficiency defined as

$$\eta_b = V_{ex}^2 / V_{ex,id}^2 = V_{ex}^2 / \{2\, g\, J\, c_p\, T_{in}\, [1 - (\, p_{ex} / P_{in,id}\,)^{exp}\,]\,\} \qquad (5)$$

where

$$exp = (\, \gamma - 1\,) / \gamma \qquad (6)$$

The blade-row exit velocities were computed using equation (5) and maintaining a constant efficiency . Values for blade-row efficiencies, which must be provided by the user, can be specified individually for each sector of each blade row. These values are usually selected so that the calculated turbine efficiency matches a known efficiency at the design point.

The stage test loss was represented by a stage test factor defined as

$$TF = \text{Actual output energy} / \text{Vector diagram energy} \qquad (7)$$

The stage test factor, which can be specified for each sector of each stage, is used to reflect losses that do not show up in the velocity diagrams. These can include clearance, disk friction, and mechanical losses. The stage test factors must be provided by the user.

Reference 1 provided little guidance for selecting values for the various loss parameters. The selected values had to yield a known design efficiency.

Model Modifications and Calibration

A review of the reference performance model resulted in concerns about several aspects of the model. The assumption of purely axial flow for the continuity calculation was questionable for high flowpath slopes such as were found in the low-pressure turbines of high bypass engines. Also, the performance model had not been adequately tested. Testing of the model against the experimental results of refs. 3-9 resulted in some additions to the reference model and recommendation of values for some of the model coefficients and exponents.

Without very detailed measurements for a given turbine, there is no obvious way to assign blade-row to blade-row and sector to sector variations for each of the loss parameters, let alone to distribute the losses among the different parameters. Therefore, the following assignments were made in order to reduce the parameters to a manageable number.

1. The stage test factor and the optimum recovery efficiency were both assumed to have values of 1 since the same effects on turbine efficiency are provided by the blade-row efficiencies and the incidence-loss cosine law, respectively.

2. All values for any given parameter were assumed equal (i.e., no spanwise or stagewise variations) in view of a lack of information concerning design details and local flow behavior during preliminary studies.

3. The rotor loss ($1 - \eta_{b,ro}$) was assumed to be twice the stator loss ($1 - \eta_{b,st}$) to reflect the larger losses occurring in the rotor due to leakages and secondary flows due to rotation.

Flow.- Introducing a flow coefficient, c_f, and treating the velocity component V_x as a meridional velocity, the continuity equation is revised to

$$w = \sum c_{f,i}\, \rho_i\, V_{x,i}\, A_{an,i} \cos \alpha_i \tag{8}$$

where the flowpath slope angle α_i for each sector is determined by the sector mean radius change across each blade row and an axial length from the axial chord correlation of reference 2. The slope used for a calculation station is the average of the sector slopes for the blade rows on either side of the station.

The improvement provided by the flowpath slope is demonstrated using the turbine of reference 9, whose flowpath has the largest slope of any of the referenced turbines. This 5-stage turbine has a meanline slope of 17 degrees over the first 3 stages and a corresponding tip slope of almost 25 degrees. With no flow coefficient correction, the inclusion of the slope in the continuity equation reduced the discrepancy between the computed and the experimental design flow rates from more than 5 percent to less than 1 percent.

The flow coefficient in equation (8) is composed of a user provided constant design coefficient, $c_{f,d}$, multiplied by a function k_f that reduces flow coefficient with increasing blade-row pressure ratio.

$$c_f = k_f\, c_{f,d} \tag{9}$$

The design coefficient is usually selected so that the calculated mass flow rate matches the known mass flow rate at design point. The correction k_f is a linear function of blade-row inlet-total to exit-static pressure ratio, pr,

$$k_f = 1 + (k_{f,lo} - 1)\,(pr - pr_{f,hi}) \,/\, (pr_{f,lo} - pr_{f,hi}) \tag{10}$$

Based on the experimental data, the values selected for the terms of equation (10) are $k_{f,lo}$=1.02, $pr_{f,lo}$=1.2, and $pr_{f,hi}$ equal to 95 percent of choking pressure ratio. The flow-coefficient correction is maintained constant at pressure ratios less than $pr_{f,lo}$ and greater than $pr_{f,hi}$.

Loss.- The blade-row inlet loss model is unchanged from equation (4), but values for optimum incidence angles and for positive and negative incidence exponents for the cosine law have been determined using the data of refs. 3-9. No single combination of values is best for all turbines, but the set of values selected herein provide a reasonable compromise for the 7 turbines studied. Recommended exponent values are a positive-incidence exponent of 3 and a negative-incidence exponent of 4.

It was observed that there seemed to be a small but definite difference in optimum incidence angle attributable to the sharpness of the turbine blading leading edge. Cooled high-pressure turbines have blunter leading edges than do uncooled low-pressure turbines. The selected optimum incidence angles are -4 degrees for low-pressure type turbines (having blades with sharper leading edges) and -6 degrees for high-pressure type turbines (having blades with blunter leading edges). The AXOD code does not provide for a direct input of optimum incidence angle; therefore, the optimum incidence effect is modeled by adding the optimum incidence angle to the design-point inlet flow angle.

The experimental data from the high-work single-stage turbines (refs. 4 and 5) showed the need for reductions in blade-row efficiency at pressure ratios beyond choke. A parabolic function of blade-row inlet-total to exit-static pressure ratio was used to provide a multiplier correction to blade-row efficiency.

$$k_\eta = 1 - (1 - k_{\eta,hi}) (pr - pr_{\eta,lo})^2 / (pr_{\eta,hi} - pr_{\eta,lo})^2 \qquad (11)$$

The values for the terms of equation (11) that best match the data are $pr_{\eta,lo}$=2.5, $pr_{\eta,hi}$=3.5, and $k_{\eta,hi}$=0.98. This blade-row efficiency applies only to pressure ratios above $pr_{\eta,lo}$ and remains constant at pressure ratios above $pr_{\eta,hi}$. The value of $pr_{\eta,hi}$ corresponds to a Mach number of about 1.4.

Model Evaluation

The revised performance model was evaluated by comparing computed off-design performance with experimental performance from seven aircraft-type turbines (refs. 3-9). Presented in Table I are the design characteristics of these turbines, three of which (refs. 5, 6, and 9) are from the Energy Efficient Engine program. They cover a wide range of both high-pressure and low-pressure turbine designs. These 20- to 30-inch tip diameter turbines vary from 1 to 5 stages and represent a five-fold variation in stage corrected work ($\Delta h/\theta$), a three-fold variation in stage work factor ($gJ\Delta h/U^2$), and a five-fold variation in flow coefficient (V_x/U). One was a two-stage cooled turbine with a cooling flow equal to 20 percent of the inlet flow. The experimental performance data were obtained in turbine component-test facilities.

Plotted in figures 1 - 7 over ranges of pressure ratio are the computed and experimental flow rates and total efficiencies for the seven turbines. Three speed lines are shown for each turbine except in figure 3, where the turbine was tested at only two speeds. The speeds ranged from as low as 40 percent of design to as high as 120 percent of design with design speed included. Pressure ratios usually ran up to choke and sometimes beyond. The two single-stage high-work turbines were choked over all or most of the range of data.

For each turbine, the flow coefficients and the blade-row efficiencies were adjusted to match the computed design-point values of flow rate and efficiency to the experimental values. All off-design performance was then computed using the revised flow and loss models described previously. The computations were performed using five equal-height annular sectors in the flowpath. As seen from figures 1 - 7, the computed values of flow and efficiency were generally within 1 percent of the experimental values and seldom beyond 2 percent. Compared to the original performance model, the revised off-design performance model reduces maximum discrepancies between computed and experimental efficiencies by a factor of about 2.

A description of the input and output for the revised off-design performance computer code AXOD is presented in the Appendix. Sample input and output are included for illustration.

SUMMARY OF RESULTS

An axial-flow turbine off-design computer code used for preliminary studies of gas turbine systems was modified and calibrated based on the experimental performance of large aircraft-type turbines. The flow- and loss-model modifications and calibrations are presented in this report. Comparisons are made between computed performances using the revised and calibrated model and experimental data for seven turbines over wide ranges of speed and pressure ratio.

The off-design performance modeling improvements made as a result of this investigation are:

1. Revision of the continuity equation to include a flowpath slope determined by using an axial-chord length correlation. The effectiveness of this change was illustrated for a turbine having a meanline flowpath slope of 17 degrees. With this revision, the discrepancy between calculated and measured design flow rates was reduced from more than 5 percent to less than 1 percent.

2. Addition of a variable flow coefficient composed of a user-defined base value and a linear function of blade-row pressure ratio that reduces the flow coefficient by 2 percent going from low pressure ratio to choke.

3. Reduction of blade-row efficiency at blade-row exit velocities beyond choke. A parabolic

function of blade-row inlet-total to exit-static pressure ratio provides a maximum reduction of 2 percent at an exit Mach number of 1.4.

4. Calibration of the incidence cosine law yielded a positive-incidence exponent of 3 and a negative-incidence exponent of 4. The optimum incidence angle was -4 degrees for low-pressure type turbines, which have blades with sharper leading edges, and -6 degrees for high-pressure type turbines, which have blades with blunter leading edges.

Computed flows and efficiencies were compared with experimental values for 7 aircraft-type high- and low-pressure turbines of varied design characteristics and operating over wide ranges of speed and pressure ratio. The computed values were generally within 1 percent of the computed values and seldom beyond 2 percent. Maximum discrepancies between computation and experiment were reduced to about half of those from the original performance model.

This report also serves as the user's manual for the revised off-design performance code AXOD. Program input and output are described and samples are included for illustration.

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Appendix

DESCRIPTION OF INPUT AND OUTPUT

This appendix presents a detailed description of input and output for program AXOD. Included to illustrate the input and output are sample inputs for a single-stage and a multi-stage turbine and sample output for the single-stage turbine.

Input

The input for each case, which is read from unit 05, consists of two title lines and k NAMELIST datasets where k is the number of turbine stages. A case is defined as one speed line for a range of pressure ratios. An input file can include multiple cases. Each of the two title lines, which are printed as page headings on the output, can contain up to 80 characters. One or both of these lines may be left blank, but they must appear as the first two records for each case.

The NAMELIST name is DATAIN. The DATAIN variables, with units and default values, are presented herein as overall input followed by stage input. Overall input is entered only once for a case and need not be repeated for subsequent cases if unchanged. Stage input is entered for each stage, unless otherwise indicated, of the first case but need not be repeated for subsequent cases if unchanged.

Input blade angles must be specified from the axial direction with the following signs:
  Stator exit and rotor inlet - positive in direction of blade speed.
  Rotor exit and stator inlet - positive in direction opposite to blade speed.

Two sample inputs are illustrated. Table IIa presents the input for the single-stage turbine whose performance is shown in figure 1. Table IIb presents the input for the two-stage cooled turbine whose performance is shown in figure 4. There are three cases in each file, one for each speed line. The first case has two title lines; the other cases have only one title line, thus requiring the inclusion of the shown blank lines. Note that very little additional data is required for speed lines beyond the first one.

Overall Input:

TTIN	Inlet total temperature (radially constant), ^{o}R. May be omitted if TTINH is input.
PTIN	Inlet total pressure (radially constant), psi. May be omitted if PTINH is input.
TTINH(I) I=1,SECT	Inlet total temperature radial distribution, ^{o}R. Overrides TTIN.

PTINH(I) I=1,SECT	Inlet total pressure radial distribution, psi. Overrides PTIN.
ALF0H(I) I=1,SECT	Inlet flow angle radial distribution, deg. (default=SECT*0.0)
WAIR	Inlet water/air ratio (default=0.0). May be omitted if RG and GAMG are input.
FAIR	Inlet fuel/air ratio (default=0.0). May be omitted if RG and GAMG are input.
PTPS	Starting value of first-stator meanline inlet-total to exit-static pressure ratio (default=1.1)
DELC	PTPS increment to initial blade-row choke (default=0.1)
DELL	PTPS increment from initial to last blade-row choke (default=0.1)
DELA	PTPS increment from last blade-row choke to exit-annulus choke (default=0.05) A value of 0.0 terminates the speed line at last-stage rotor choke.
STG	Number of stages, maximum=8.
SECT	Number of radial sectors, maximum=6. (default=1.0)
EXPN	Negative-incidence exponent (default=4.0)
EXPP	Positive-incidence exponent (default=3.0)
RG	Gas constant, ft-lbf/(lbm-^{o}R). Omit for internal computation of RG and GAMG for air.
PAF	Profile (temp & press) averaging switch for next stage inlet (default=0.0) 0.0 - Radially uniform 1.0 - Maintain existing radial profiles 2.0 - Maintain temperature and smooth pressure
SLI	Stage loss-value switch for SREC, SETA, SCF, RREC, RETA, RCF, & RTF (default=1.0) 0.0 - Data to be input for all stages 1.0 - First-stage values used for all stages
AACS	Turbine-exit axial Mach number for termination of speed line (default=1.0)

VCTD	Output switch (default=0.0) -1.0 - Overall performance only 0.0 - Overall performance plus meanline values of key variables 1.0 - Overall performance plus all variable values for all radial sectors
PCNH(I) I=1,SECT	Sector height distribution, fraction of annulus height (default=1.0) (Not cumulative, sum of i values must equal 1.0)
WG	Mass flow rate, lb/sec. Used for design option only (default=0.0) NOTE: A non-zero value triggers the design option.
EPR	Switch for high pressure-ratio correction to blade-row efficiency (default=1.0) 0.0 - Off 1.0 - On
WTOL	Tolerance for mass-flow rate convergence (default=1.e-5)
RHOTOL	Tolerance for density convergence (default=1.e-4)
PRTOL	Tolerance for pressure ratio convergence (default=1.e-6)
TRLOOP	Debug output switch for iteration control variables (default=0.0) 0.0 - Off 1.0 - On
TRDIAG	Debug output switch for flow and state variables (default=0.0) 0.0 - None 1.0 - Station 0 (stator inlet) 2.0 - Station 1 (stator exit) 3.0 - Station 1A (rotor inlet) 4.0 - Station 2 (rotor exit) 5.0 - Station 2A (stage exit) 6.0 - All stations - after each station calculation 7.0 - All stations - after overall performance calculation
PFIND	Selected value of turbine total pressure ratio to be searched for. Omit if not used.
DHFIND	Selected value of turbine specific work to be searched for. Omit if not used.

IAR Switch for axial-chord length (default=0)

0 - No slope used for continuity (i.e., axial flow)
1 - High aspect-ratio blading
2 - Mid aspect-ratio blading
3 - Low aspect-ratio blading
10 - 20 Fractional values between IAR=1 and IAR=2
20 - 30 Fractional values between IAR=2 and IAR=3

ICYL Switch for blading angle definition (default=0)

0 - Input blade angles are on a flowpath surface with slope defined by IAR
1 - Input blade angles are on a cylindrical surface

ICF Switch for flow coefficient variation (default=0)

0 - Flow coefficient varies with blade-row pressure ratio
1 - Flow coefficient constant

ENDPLT Switch for writing a map file in NEPP (ref. 10) format (default=0.0)

0.0 - No
1.0 - Yes

ENDJOB Switch for last case (default=0.0)

0.0 - More cases to follow
1.0 - Last case

Stage Input: The J subscripts refer to the 5 stage calculation stations, which are stator inlet, stator exit, rotor inlet, rotor exit, and stage exit/next stator inlet. The I subscripts refer to the radius centers of the SECT annular sectors.

STAGE Stage number (not number of stages)

RPM Stage rotative speed, rev/min. Will remain constant for subsequent stages until changed

GAMG(J) J=1,5 Specific heat ratio. Omit if RG is omitted as it is internally computed (for air)

DR(J) J=1,5 Hub diameter, inches

DT(J) J=1,5 Tip diameter, inches

RWG(J) J=1,5	Ratio of station mass-flow rate to turbine inlet mass-flow rate. For the first stage, RWG(1) must equal 1.0. For subsequent stages, RWG(1) must equal RWG(5) of the previous stage.
TWG(J) J=1,5	Temperature of the coolant specified by RWG, °R. Input only for stations where coolant is added.
PWG(J) J=1,5	Pressure of the coolant specified by RWG, psi. Input only for stations where where coolant is added.
SDIA(I) I=1,SECT	Stator vane inlet angle, deg. Add optimum incidence angle to design angle. Omit for design option.
SDEA(I) I=1,SECT	Stator vane exit angle, deg. Omit if SPA option is used or for design option.
SPA(I) I=1,SECT	Stator throat area per unit height, sq in./in. Omit if SDEA option is used.
SESTH	Ratio of blade height at stator exit to blade height at stator throat. Omit if SDEA option is used.
RDIA(I) I=1,SECT	Rotor blade inlet angle, deg. Add optimum incidence angle to design angle. Omit for design option.
RDEA(I) I=1,SECT	Rotor blade exit angle, deg. Omit if RPA option is used or for design option.
RPA(I) I=1,SECT	Rotor throat area per unit height, sq in./in. Omit if RDEA option is used.
RERTH	Ratio of blade height at rotor exit to blade height at rotor throat. Omit if RDEA option is used.
SREC(I) I=1,SECT	Stator inlet recovery efficiency, decimal. Input only for first stage if SLI=1.0. (default=SECT*1.0)
SETA(I) I=1,SECT	Stator efficiency, decimal. Input only for first stage if SLI=1.0.
SCF(I) I=1,SECT	Stator flow coefficient, decimal. Input only for first stage if SLI=1.0. (default=SECT*1.0)

RREC(I) I=1,SECT	Rotor inlet recovery efficiency, decimal. Input only for first stage if SLI=1.0. (default=SECT*1.0)
RETA(I) I=1,SECT	Rotor efficiency, decimal. Input only for first stage if SLI=1.0.
RCF(I) I=1,SECT	Rotor flow coefficient, decimal. Input only for first stage if SLI=1.0. (default=SECT*1.0)
RTF(I) I=1,SECT	Rotor test factor, decimal. Input only for first stage if SLI=1.0. (default=SECT*1.0)
RVU1(I) I=1,SECT	Design stator-exit angular momemtum (radius * tangential velocity), in.-ft/sec. Input for design option only.
RVU2(I) I=1,SECT	Design rotor-exit angular momemtum (radius * tangential velocity), in.-ft/sec. Input for design option only.
ENDSTG	Switch for last stage (default=0.0) 0.0 - Not last stage 1.0 - Last stage

Output

Three levels of output are available as specified by the input variable VCTD. All levels provide an input echo. The lowest level (VCTD=-1.0) prints only the overall performance. The next level (VCTD=0.0) adds stage meanline variables to the output. The highest level (VCTD=1.0) adds the printout of all variables for all stations and all annular sectors.

Presented in table III is the sample output that corresponds to the sample input of table IIa. This is the highest-level output, but presents computed results for only the first pressure-ratio point on the first speed line. The full output for this case would have about 30 points on each speed line. Shown on the first page of table III is the input echo with the variables all being defined in the Input section. The next page of this table presents the stage and overall performance results that are printed for the mid-level output. Only the overall performance is printed at the lowest level. The last two pages display the detailed interstage performance printed for the highest level in addition to the overall and stage performance. In addition to detailed output presented for the five annular sectors, extrapolated values are printed for the hub and the tip.

The output variables shown in table III are defined in this section. The calculation stations and radial locations are identified as follows:

0 - Stator inlet
1 - Stator exit
1A - Rotor inlet
2 - Rotor exit
2A - Stage exit
P - Pitchline (i.e., meanline)
R - Root
RT - Root
TIP - Tip

The output variables are listed in the order of their first appearance.

TT	Total temperature, ^{o}R
PT	Total pressure, psi
WG	Mass flow rate, lb/sec
DEL H	Specific work, Btu/lb
WRT/P	Corrected mass flow rate at stage or turbine inlet ($w\sqrt{T}/P$), (lb/sec)($^{o}R)^{1/2}$/psi
DH/T	Corrected specific work ($\Delta h_{tt}/T$), Btu/(lb)(^{o}R)
N/RT	Corrected rotative speed $N/\sqrt{T}$, rpm/$^{o}R^{1/2}$
ETA TT	Total efficiency
ETA TS	Static efficiency
ETA AT	Rating efficiency
PT0/PS1	Stator inlet-total to exit-static pressure ratio
PT0/PT2	Stage or turbine inlet-total to exit-total pressure ratio
PT0/PS2	Stage or turbine inlet-total to exit-static pressure ratio
PTR1A/PS2	Rotor inlet-relative-total to exit static pressure ratio
TT2/TT0	Stage exit-total to inlet-total temperature ratio
TTR1/TT0	Rotor-inlet-relative-total to stage-inlet-total temperature ratio
PS	Static pressure, psi
TTR	Relative total temperature, ^{o}R
PTR	Relative total pressure, psi
UP/VI	Ratio of pitchline blade speed to stage isentropic velocity, $U_p/\sqrt{(2gJ\Delta h_{ts,id})}$
UR/VI	Ratio of root blade speed to stage isentropic velocity, $U_r/\sqrt{(2gJ\Delta h_{ts,id})}$
W.F.	Stage or turbine work factor, $gJ\Delta h_{tt}/U^2$
RX	Stage reaction, ratio of rotor-to-stage static enthalpy drops
ALPH(A)	Absolute flow angle, deg
I	Incidence angle, deg
BETA	Relative flow angle, deg
DBETA	Rotor turning angle, deg
M	Absolute Mach number
MR	Relative Mach number

E/TH CR	Stage or turbine equivalent work, $\Delta h_{tt}/\theta$, Btu/lb
N/RTH CR	Stage or turbine equivalent speed, $N/\sqrt{\theta}$, rpm
WRTHCRE/D	Equivalent mass flow rate, $w\sqrt{\theta}\varepsilon/\delta$, lb/sec
RPM	Rotative speed, rev/min
MF	Axial Mach number
PT/T EQ	Turbine equivalent inlet-total to exit-total pressure ratio
PT/S EQ	Turbine equivalent inlet-total to exit-static pressure ratio
PT/PAT2	Turbine inlet-total to exit-axial-total pressure ratio
ETA TTRP	Turbine total efficiency based on first-rotor inlet ideal enthalpy
WNE/60D	Turbine equivalent flow-speed parameter, $wN\varepsilon/60\delta$, (lb)(rev)/sec^2
HP	Turbine power output, horsepower
EQ WG0	Equivalent mass flow rate, $w\sqrt{\theta}\varepsilon/\delta$, lb/sec
TORQUE	Turbine torque, lb-ft
TOR/P	Turbine corrected torque, T/P, ft-in^2
EQ TOR	Turbine equivalent torque, $T\varepsilon/\delta$, lb-ft
U/VIS	Ratio of mean blade speed to turbine isentropic velocity, $U_p/\sqrt{(2gJ\Delta h_{ts,id})}$
DIAM	Diameter, inches
SLOP(E)	Sector geometric flowpath slope
V	Absolute velocity, ft/sec
VU	Absloute velocity tangential component, ft/sec
VZ	Absolute velocity meridional component, ft/sec
TS	Static temperature, ^oR
DENS	Density, lb/ft^3
DEL A	Stator turning angle, deg
ZWI INC	Zweifel incompressible blade loading coefficient
ETA S	Stator efficiency
FTAN/IN	Stator or rotor tangential blade loading per unit height, lb/in
F TAN	Stator or rotor total tangential blade loading, lb
FAX/IN	Stator or rotor axial blade loading per unit height, lb/in
F AX	Stator or rotor total axial blade loading, lb
F DRUM	Axial forces on stator or rotor endwall surfaces, lb
R	Relative velocity, ft/sec
RU	Relative velocity tangential component, ft/sec
U	Blade speed, ft/sec
PSI	Sector work coefficient, $gJ\Delta h_{tt}/2U^2$
ETA R	Rotor efficiency

TABLE I
DESIGN CHARACTERISTICS OF TURBINES USED FOR
OFF-DESIGN PERFORMANCE MODEL EVALUATION

Number of stages	Total pressure ratio	Maximum corrected tip speed, ft/sec	Stage average corrected work, Btu/lb	Stage average work factor	Average flow coefficient	Hub diameter in/out, inches	Tip diameter in/out, inches	Exit radius ratio	Reference
1	1.8	577	17.0	1.7	0.67	22.0/22.0	30.0/30.0	0.73	3
1	3.4	705	33.0	1.9	0.64	17.0/17.0	20.0/20.0	0.85	4
1	4.2	837	37.8	1.6	0.35	20.4/20.3	24.0/24.1	0.84	5
2	5.0	690	21.9	1.3	0.46	24.9/24.5	29.4/30.0	0.82	6 *
3	3.5	393	11.0	3.0	1.41	17.8/17.8	22.1/28.4	0.63	7
3.5	2.3	290	7.5	4.0	1.75	15.8/13.0	23.4/26.2	0.50	8
5	4.4	437	7.9	2.6	1.02	17.2/19.2	21.6/31.2	0.62	9

* Cooled - coolant flow is 20% of turbine inlet flow

TABLE IIa.—SAMPLE INPUT FOR SINGLE-STAGE TURBINE

```
NASA ONE-STAGE TURBINE - TN D-4389
100 PERCENT SPEED
&DATAIN STAGE=1.,
TTIN=518.7,PTIN=14.696,IAR=2,PTPS=1.25,DELC=.01,DELL=0.1,DELA=0.0,
STG=1.,SECT=5.,PCNH=5*0.2,VCTD=1.,RG=53.35,RPM=4407.4,
GAMG=5*1.4,RWG=5*1.0,EXPN=4.,EXPP=3.,DR=5*22.,DT=5*30.,
SDIA=5*-6.,SDEA=69.6,68.3,67.0,65.8,64.5,
SETA=5*.9628,SREC=5*1.0,SCF=5*.990,
RDIA=45.5,38.0,30.4,21.5,11.5,RDEA=56.35,57.30,58.26,59.19,60.12,
RETA=5*.9256,RTF=5*1.0,RREC=5*1.0,RCF=5*.990,
ENDPLT=1.0,ENDSTG=1. &END

70 PERCENT SPEED
&DATAIN PTPS=1.3,RPM=3085.2,VCTD=-1.,
ENDSTG=1.0 &END

40 PERCENT SPEED
&DATAIN PTPS=1.4,RPM=1763.0,
ENDSTG=1.0,ENDJOB=1. &END
```

TABLE IIb.—SAMPLE INPUT FOR MULTI-STAGE COOLED TURBINE

```
NASA/GE EEE HPT TWO-STAGE COOLED TURBINE
101.6 PERCENT SPEED
&DATAIN STAGE=1.,ENDJOB=0.,ENDPLT=1.,
TTIN=1283.,PTIN=50.0,EPR=1.,AACS=.55,
PTPS=1.535,DELC=.001,DELL=.1,DELA=0.1,
STG=2.,SECT=5.,PCNH=5*0.2,VCTD=-1.,
RPM=8416.4,SLI=1.0,IAR=20,ICYL=1,
EXPN=4.,EXPP=3.0,
DR=24.94,25.65,25.60,25.46,25.06,
DT=29.36,28.80,28.82,28.82,29.16,
SDIA=5*-6.,SETA=5*.9530,SREC=5*1.0,SDEA=73.32,73.76,74.2,74.68,75.16,
RDIA=35.0,37.2,37.2,33.6,21.5,RETA=5*.9060,
RDEA=66.3,66.9,66.9,66.3,65.2,RTF=5*1.0,RREC=5*1.0,
RWG=1.0,1.0895,1.105,1.1759,1.1759,TWG=0.0,615.,620.,622.,0.0,
PWG=0.0,50.5,38.6,50.3,0.0,SCF=5*.976,RCF=5*.976,
ENDSTG=0. &END
&DATAIN STAGE=2.,ENDSTG=1.,
DR=25.06,24.58,24.50,24.50,24.50,
DT=29.16,29.96,30.00,30.00,30.00,
RWG=1.1759,4*1.2007,TWG=0.0,640.,3*0.0,PWG=0.0,23.7,3*0.0,
SDIA=10.3,14.3,15.8,12.0,6.1,SDEA=5*69.,
RDIA=23.2,17.8,11.0,0.7,-13.6,RDEA=5*59.8,
&END

76.2 PERCENT SPEED
&DATAIN STAGE=1.0,PTPS=1.590,RPM=6312.3,ENDSTG=0.0 &END
&DATAIN STAGE=2.,VCTD=-1.,ENDSTG=1. &END

59.3 PERCENT SPEED
&DATAIN STAGE=1.0,PTPS=1.62,RPM=4912.4,ENDSTG=0.0 &END
&DATAIN STAGE=2.,VCTD=-1.,ENDSTG=1.,ENDJOB=1. &END
```

TABLE III.—SAMPLE OUTPUT

```
                          TURBINE COMPUTER PROGRAM
    NASA ONE-STAGE TURBINE - TN D-4389
    100 PERCENT SPEED
*DATAIN
  TTIN=    518.700   PTIN=    14.696  WAIR=        .000 FAIR=        .000
  PTPS=      1.250   DELC=      .010  DELL=        .100 DELA=        .000
   STG=      1.000   SECT=     5.000  EXPN=       4.000 EXPP=       3.000
    RG=     53.350    PAF=      .000   SLI=       1.000 AACS=       1.000
   RPM=   4407.400   VCTD=     1.000 EXPRE=        .000   WG=        .000
ENDSTG=      1.000 ENDJOB=      .000DHFIND= 10000.000PFIND=    1000.000
   IAR=          2    EPR=     1.000
                          INLET RADIAL PROFILES
PCNH=     .200      .200      .200      .200      .200      .000



                            STANDARD OPTION
 STAGE=  1                      AXIAL STATIONS
         STA. 0    STA. 1    STA.1A    STA. 2   STA. 2A
  GAMG=   1.400     1.400     1.400     1.400     1.400        .000
    DR=  22.000    22.000    22.000    22.000    22.000        .000
    DT=  30.000    30.000    30.000    30.000    30.000        .000
   RWG=   1.000     1.000     1.000     1.000     1.000        .000
   TWG=      .0        .0        .0        .0        .0          .0
   PWG=     .00       .00       .00       .00       .00         .00
 SESTH=    .000  RERTH=     .000   RPM=  4407.4

                   STATOR RADIAL DISTRIBUTIONS
  SDIA=  -6.000    -6.000    -6.000    -6.000    -6.000        .000
  SDEA=  69.600    68.300    67.000    65.800    64.500        .000
  SREC=   1.000     1.000     1.000     1.000     1.000        .000
  SETA=    .963      .963      .963      .963      .963        .000
   SCF=    .990      .990      .990      .990      .990        .000
   SPA=    .000      .000      .000      .000      .000        .000
  RVU1=      .0        .0        .0        .0        .0          .0

                   ROTOR RADIAL DISTRIBUTIONS
  RDIA=  45.500    38.000    30.400    21.500    11.500        .000
  RDEA=  56.350    57.300    58.260    59.190    60.120        .000
  RREC=   1.000     1.000     1.000     1.000     1.000        .000
  RETA=    .926      .926      .926      .926      .926        .000
   RCF=    .990      .990      .990      .990      .990        .000
   RTF=   1.000     1.000     1.000     1.000     1.000        .000
   RPA=    .000      .000      .000      .000      .000        .000
  RVU2=      .0        .0        .0        .0        .0          .0

TURBINE LENGTH =   3.51 INCHES
```

TABLE III.—Continued

NASA TURBINE COMPUTER PROGRAM
NASA ONE-STAGE TURBINE - TN D-4389
100 PERCENT SPEED

CASE 1. 1

STAGE PERFORMANCE

	STAGE 1	STAGE 2	STAGE 3	STAGE 4	STAGE 5	STAGE 6	STAGE 7	STAGE 8
TT 0	518.7							
PT 0	14.696							
WG 0	35.341							
DEL H	9.622							
WRT/P	54.769							
DH/T	.01855							
N/RT	193.519							
ETA TT	.91332							
ETA TS	.80057							
ETA AT	.90306							
PT0/PS1	1.250							
PT0/PT2	1.363							
PT0/PS2	1.427							
PTR1A/PS2	1.176							
TT2/TT0	.92268							
TTR1/TT0	.95020							
PS 1	11.752							
TTR 1	492.9							
PTR 1	12.116							
PS 2	10.300							
TT 2	478.6							
PT 2	10.784							
UP/VI	.64452							
UR/VI	.54536							
W.F. P	.96361							
W.F. R	1.34587							
RX P	.35936							
RX R	.15371							
ALPHA 0	.000							
I STATOR	6.000							
BETA 1A	14.244							
I ROTOR	-16.156							
ALPHA 2	-16.164							
DBETA R	96.254							
M 1	.56226							
M1 RT	.65392							
MR 1A	.22667							
MR1A RT	.31222							
MR 2	.46802							
MR2 TIP	.52611							
E/TH CR	9.622							
N/RTH CR	4407.4							
WRTHCRE/D	35.341							
RPM	4407.4							
MF 2A	.24622							

OVERALL PERFORMANCE

W.F. P	.96361	W.F. R	1.34587	DEL H	9.62213	WNE/60D	2596.030	TORQUE	573.185
WRT/P	54.76934	N/RT	193.519	DH/T	.01855	N/RTH CR	4407.367	TOR/P	39.00280
PT0/PT2	1.36282	PT0/PS2	1.42686	PT/PAT2	1.36792	E/TH CR	9.62199	EQ TOR	573.18512
ETA TT	.91332	ETA TS	.80057	ETA TTRP	.91332	HP	481.008	U/VIS	.64452
PT/T EQ	1.36282	PT/S EQ	1.42686	WG 0	35.3410	EQ WG0	35.34124	PT0/PS1	1.25000

TABLE III.—Continued

TURBINE COMPUTER PROGRAM
NASA ONE-STAGE TURBINE - TN D-4389
100 PERCENT SPEED

CASE 1. 1
INTER-STAGE PERFORMANCE

STA 0	STATOR	INLET		STAGE	1.		
DIAM 0	22.000	22.908	24.659	26.294	27.832	29.290	30.000
SLOPE 0		.00	.00	.00	.00	.00	
WG 0		7.068	7.068	7.068	7.068	7.068	
TT 0	518.7	518.7	518.7	518.7	518.7	518.7	518.7
PT 0	14.696	14.696	14.696	14.696	14.696	14.696	14.696
ALPHA 0	.000	.000	.000	.000	.000	.000	.000
I STA 0	6.000	6.000	6.000	6.000	6.000	6.000	6.000
V 0	207.230	207.230	207.230	207.230	207.230	207.230	207.230
VU 0	.000	.000	.000	.000	.000	.000	.000
VZ 0	207.230	207.230	207.230	207.230	207.230	207.230	207.230
TS 0	515.1	515.1	515.1	515.1	515.1	515.1	515.1
PS 0	14.345	14.345	14.345	14.345	14.345	14.345	14.345
DENS 0	.07516	.07516	.07516	.07516	.07516	.07516	.07516
M 0	.18626	.18626	.18626	.18626	.18626	.18626	.18626
STA 1	STATOR	EXIT					
DIAM 1	22.000	22.800	24.400	26.000	27.600	29.200	30.000
SLOPE 1		.00	.00	.00	.00	.00	
WG 1		5.926	6.501	7.077	7.627	8.210	
TT 1	518.7	518.7	518.7	518.7	518.7	518.7	518.7
ALPHA 1	70.214	69.599	68.299	66.999	65.799	64.499	63.864
DEL A	70.214	69.599	68.299	66.999	65.799	64.499	63.864
V 1	700.727	678.991	641.467	608.791	580.233	554.968	542.943
VU 1	659.358	636.401	596.004	560.390	529.238	500.902	487.427
VZ 1	237.204	236.690	237.192	237.884	237.861	238.929	239.169
TS 1	477.8	480.3	484.5	487.9	490.7	493.1	494.2
PS 1	10.904	11.105	11.456	11.752	12.002	12.216	12.312
DENS 1	.06159	.06240	.06383	.06502	.06602	.06687	.06725
M 1	.65392	.63199	.59452	.56226	.53434	.50984	.49823
ZWI INC	.5953	.6107	.6654	.7194	.7702	.8223	.8368
ETA S	.9628	.9628	.9628	.9628	.9628	.9628	.9628
	STATOR	FORCES					
AVG DIA	22.000	22.800	24.400	26.000	27.600	29.200	30.000
FTAN/IN	-151.8	-146.5	-150.5	-154.1	-156.8	-159.8	-155.5
			F TAN	-614.4			
FAX/IN	256.8	241.6	221.1	203.3	188.2	174.5	166.1
			F AX	824.3			
F DRUM	.0						.0

TABLE III.—Concluded

TURBINE COMPUTER PROGRAM
NASA ONE-STAGE TURBINE - TN D-4389
100 PERCENT SPEED
CASE 1. 1
INTER-STAGE PERFORMANCE

STA 1A	ROTOR	INLET		STAGE 1			
DIAM 1A	22.000	22.800	24.400	26.000	27.600	29.200	30.000
SLOP 1A		.00	.00	.00	.00	.00	
WG 1A		5.926	6.501	7.077	7.627	8.210	
TTR 1A	487.2	488.3	490.5	492.9	495.4	498.1	499.6
PTR 1A	11.653	11.747	11.933	12.116	12.304	12.507	12.626
BETA 1A	44.888	39.905	28.123	14.244	-.370	-14.241	-20.516
I ROTOR	-5.353	-5.595	-9.877	-16.156	-21.869	-25.741	-26.937
R 1A	334.803	308.547	268.944	245.429	237.866	246.505	255.366
RU 1A	236.278	197.936	126.770	60.387	-1.535	-60.641	-89.500
MR 1A	.31244	.28719	.24926	.22667	.21905	.22646	.23434
U 1A	423.080	438.464	469.234	500.003	530.773	561.542	576.927
STA 2	ROTOR	EXIT					
DIAM 2	22.000	22.800	24.400	26.000	27.600	29.200	30.000
SLOPE 2		.00	.00	.00	.00	.00	
WG 2		5.890	6.498	7.077	7.651	8.225	
BETA 2	55.886	56.349	57.299	58.259	59.189	60.119	60.600
DBETA	100.774	96.254	85.422	72.503	58.819	45.878	40.084
R 2	450.717	448.944	474.740	498.547	521.859	545.677	535.821
RU 2	373.157	373.714	399.494	423.982	448.205	473.136	466.817
MR 2	.42345	.42177	.44589	.46802	.48963	.51164	.50238
U 2	423.080	438.464	469.234	500.003	530.773	561.542	576.927
RX	.15622	.20533	.28979	.35936	.41732	.46622	.48781
DEL H	10.299	10.011	9.862	9.674	9.469	9.252	8.695
PSI	.72024	.65188	.56073	.48440	.42075	.36729	.32701
ETA TT	.95901	.93227	.92739	.91760	.90542	.89157	.83787
ETA TS	.85465	.83082	.81942	.80478	.78857	.77143	.72496
ETA AT	.95164	.92510	.91905	.90774	.89388	.87848	.82557
ZWI INC	1.5467	1.4361	1.2212	1.0353	.8764	.7380	.6688
ETA R	.9256	.9256	.9256	.9256	.9256	.9256	.9256
	ROTOR	FORCES					
AVG DIA	22.000	22.800	24.400	26.000	27.600	29.200	30.000
FTAN/IN	139.5	130.8	132.9	133.2	132.8	131.8	120.6
			F TAN	528.6			
FAX/IN	40.6	55.6	84.2	112.0	138.5	164.5	175.9
			F AX	443.1			
F DRUM	.0						.0
STA 2A	STAGE	EXIT					
DIAM 2A	22.000	22.800	24.400	26.000	27.600	29.200	30.000
SLOP 2A		.00	.00	.00	.00	.00	
WG 2A		5.890	6.498	7.077	7.651	8.225	
PT 2A	10.716	10.716	10.751	10.781	10.809	10.836	10.836
TT 2A	477.0	477.0	477.6	478.4	479.2	480.1	480.1
V 2A	257.666	257.063	265.793	273.071	279.762	285.870	285.150
VU 2A	-49.923	-64.750	-69.740	-76.021	-82.568	-88.407	-110.110
ALPH 2A	-11.172	-14.589	-15.212	-16.164	-17.166	-18.014	-22.715
MF 2A	.23749	.23372	.24090	.24622	.25079	.25490	.24662
VZ 2A	252.783	248.774	256.480	262.276	267.300	271.856	263.033
TS 2A	471.5	471.5	471.7	472.2	472.7	473.3	473.4
PS 2A	10.288	10.290	10.295	10.300	10.304	10.308	10.311
DENS 2A	.05890	.05891	.05891	.05888	.05883	.05878	.05879
M 2A	.24208	.24150	.24964	.25635	.26248	.26804	.26735

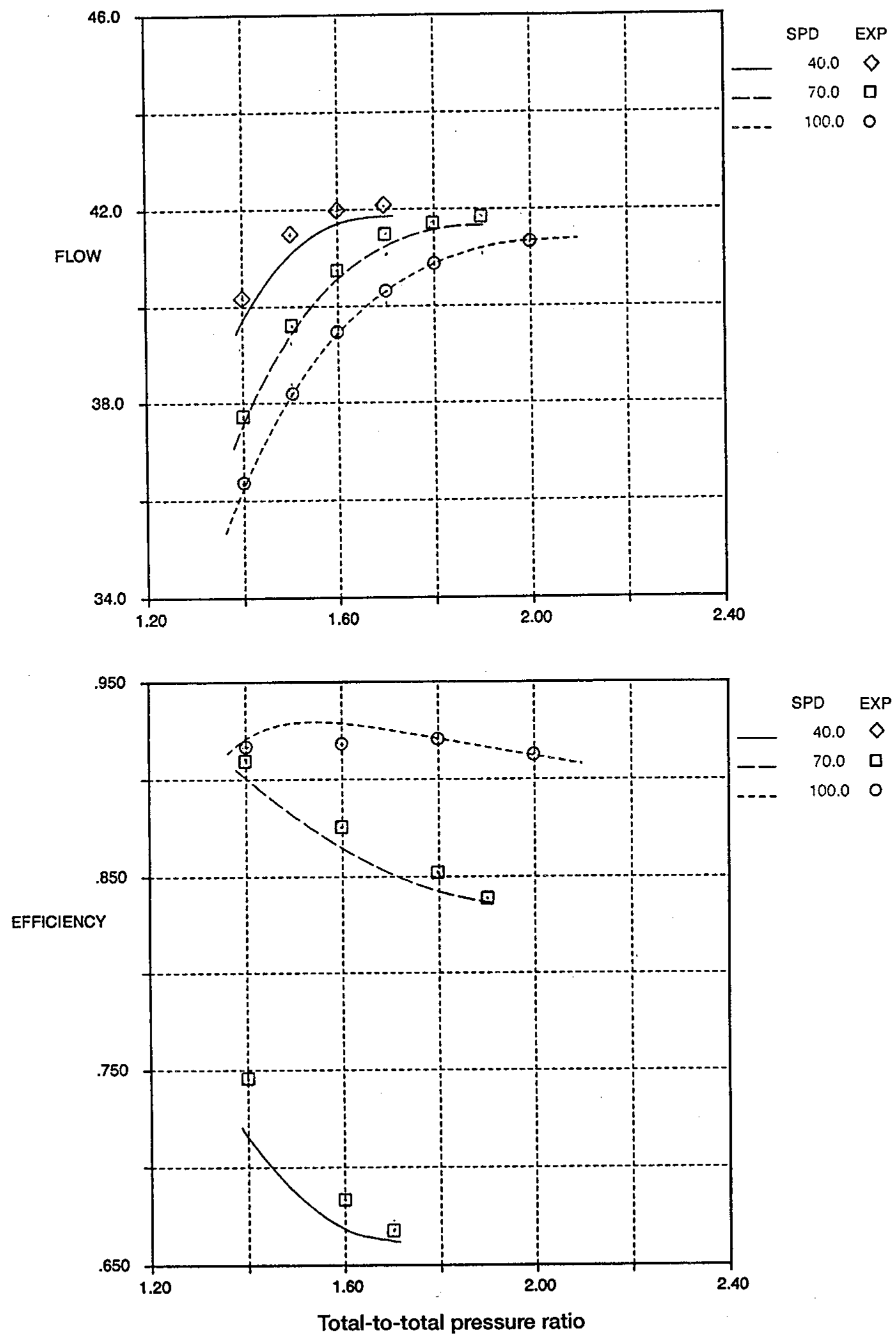

Figure 1.—Comparison of computed and measured performance for single-stage turbine of ref. 3.

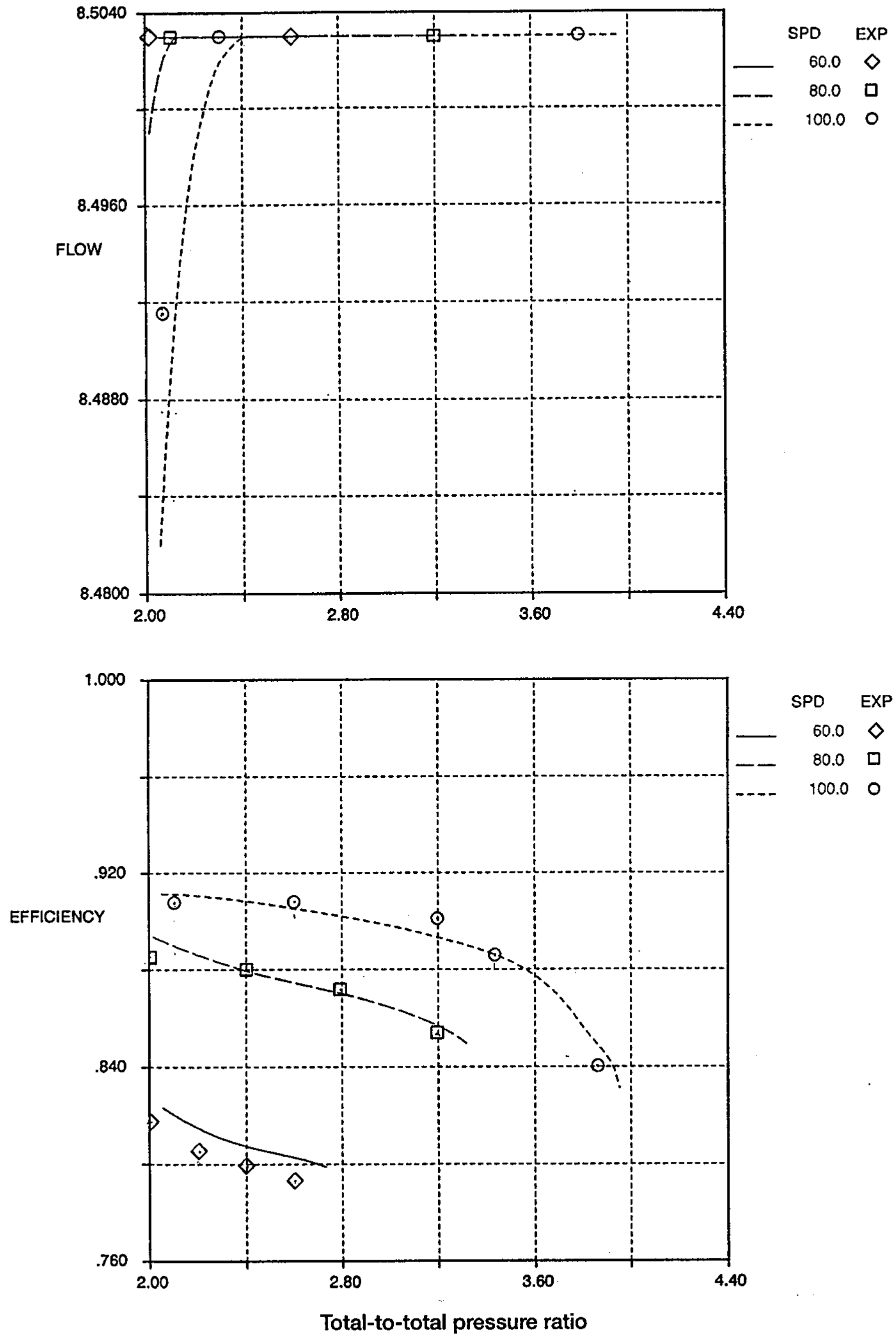

Figure 2.—Comparison of computed and measured performance for single-stage turbine of ref. 4.

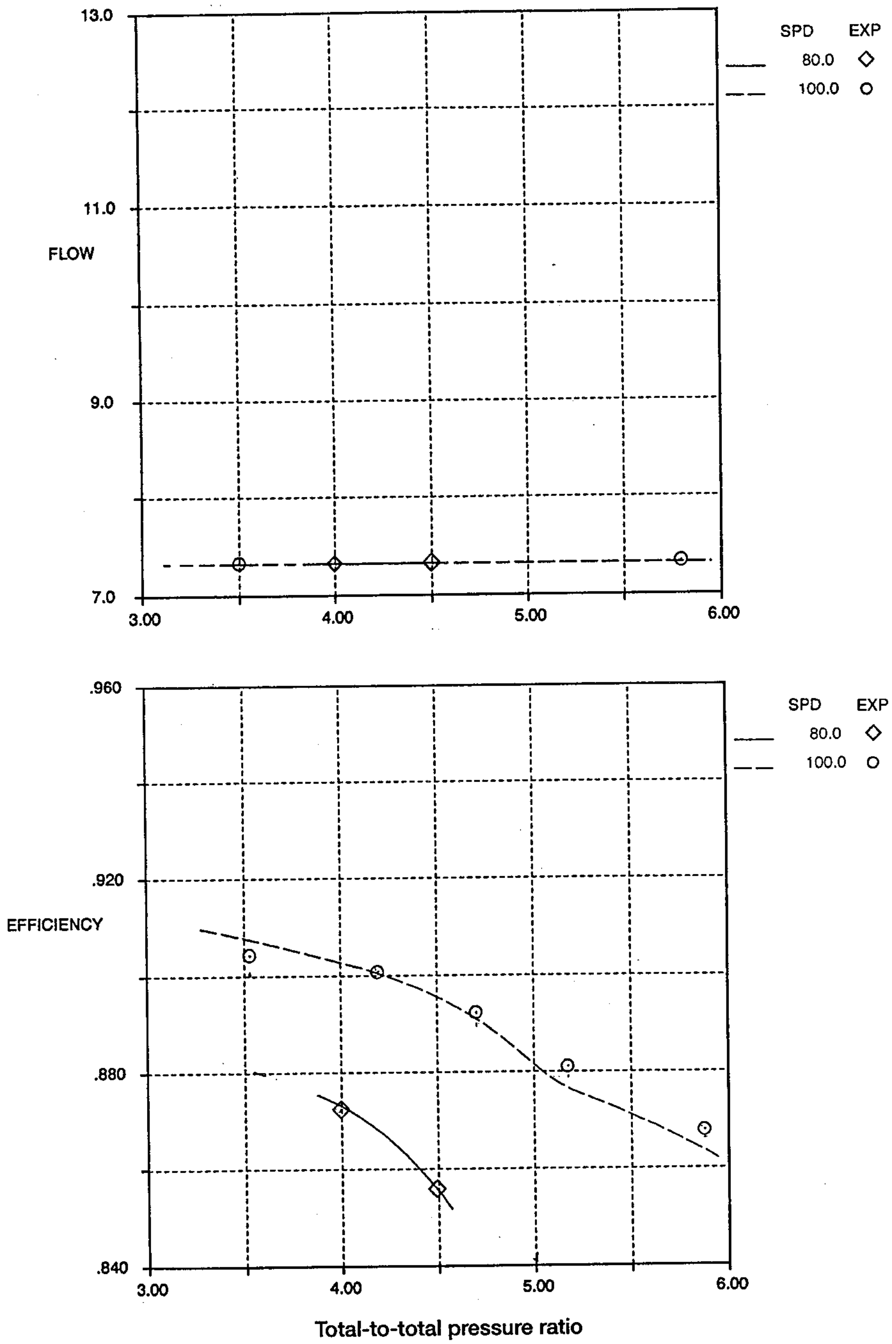

Figure 3.—Comparison of computed and measured performance for single-stage turbine of ref. 5.

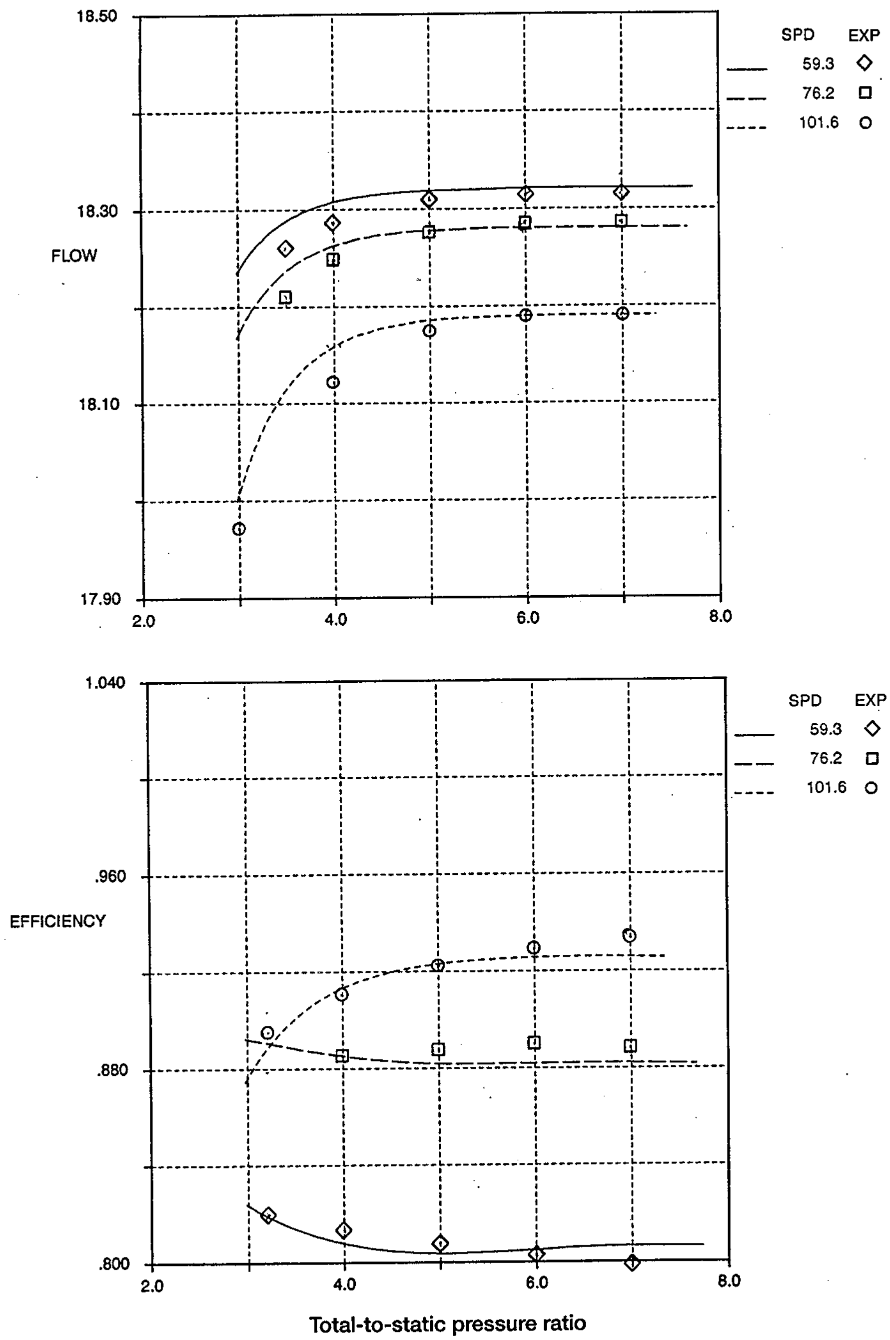

Figure 4.—Comparison of computed and measured performance for two-stage turbine of ref. 6.

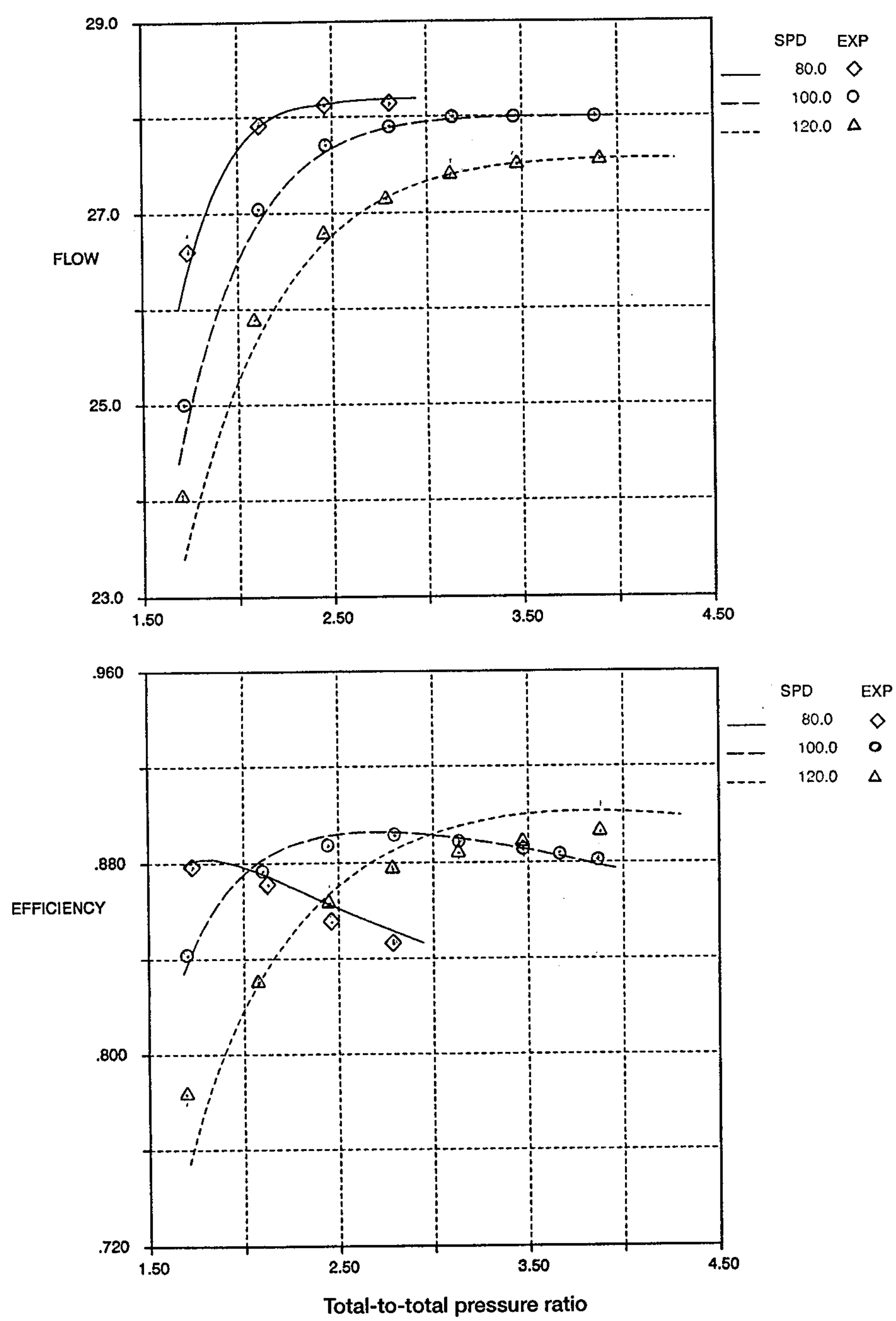

Figure 5.—Comparison of computed and measured performance for three-stage turbine of ref. 7.

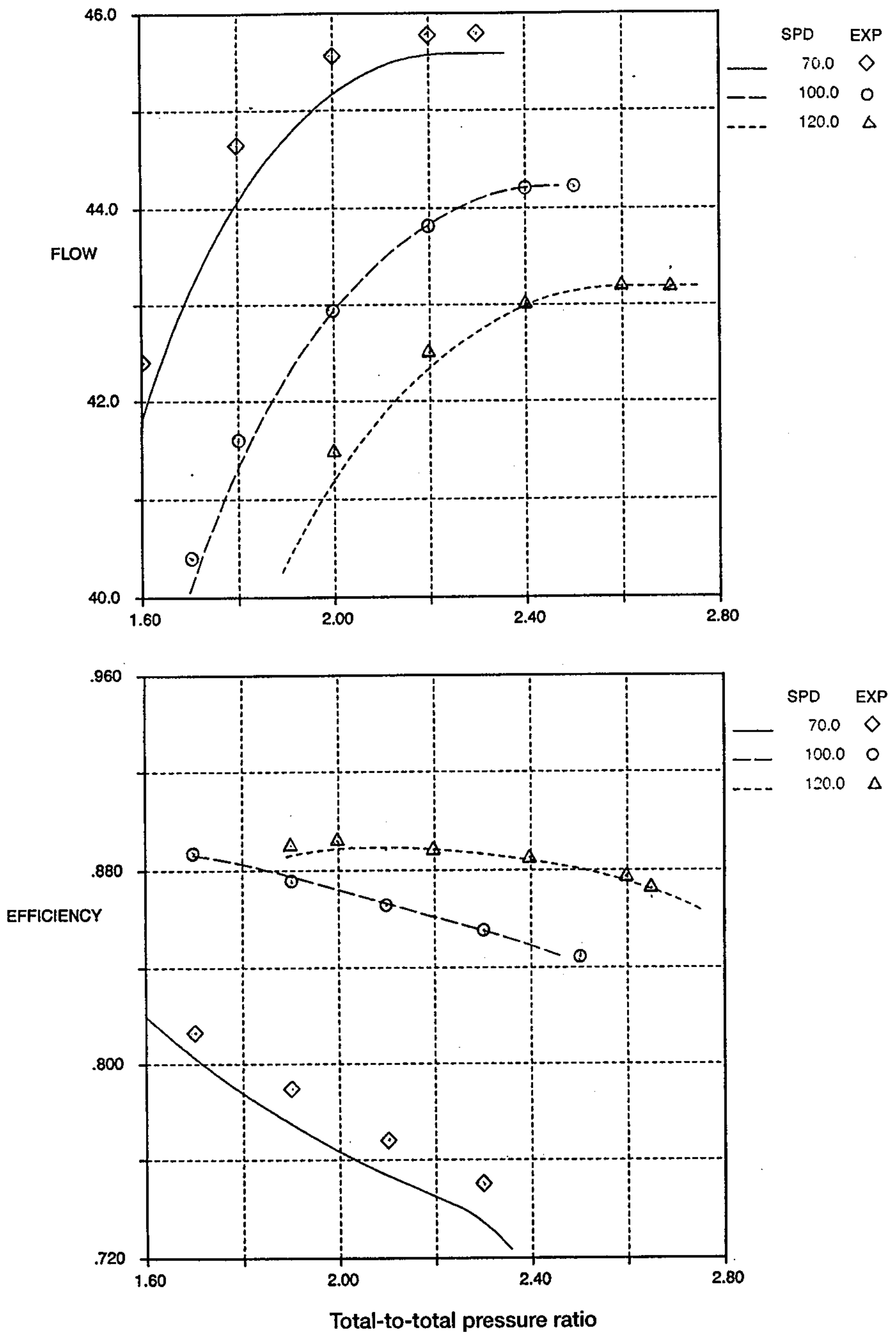

Figure 6.—Comparison of computed and measured performance for three and one half-stage turbine of ref. 8.

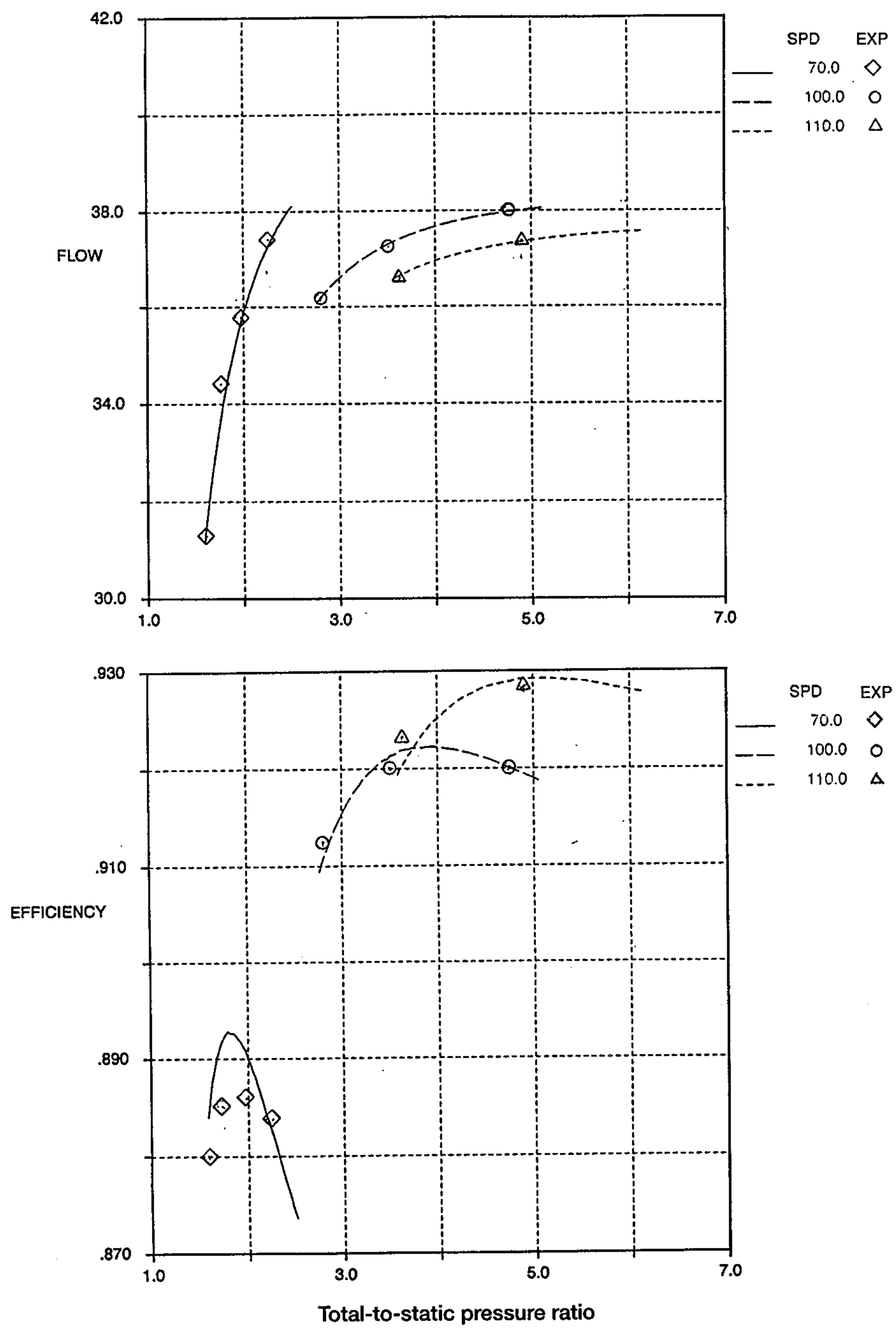

Figure 7.—Comparison of computed and measured performance for five-stage turbine of ref. 9.

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An axial-flow turbine off-design performance computer code used for preliminary studies of gas turbine systems was modified and calibrated based on the experimental performance of large aircraft-type turbines. The flow- and loss-model modifications and calibrations are presented in this report. Comparisons are made between computed performances and experimental data for seven turbines over wide ranges of speed and pressure ratio. This report also serves as the users manual for the revised code, which is named AXOD.

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